THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

THE RELATIONSHIP OF ELASTIC MODULUS TO MAT DENSITY

Project 2733

Report Five

A Progress Report

to

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THE RELATIONSHIP OF ELASTIC MODULUS TO MAT DENSITY

SUMMARY

The bending modulus and z-tensile strengths of fibrous mats of 1800-2000 g./m.^{2} basis weight prepared from bleached southern pine dry-lap kraft pulp were determined as functions of wet mat compacting pressure applied for 900 seconds. The pulps studied included the original unbeaten whole pulp, a classified unbeaten pulp, whole unbeaten pulp to which 10% of fines had been added, and pulps at two different refining levels.

The densities of the compacted wet mats at quasi-equilibrium were of similar magnitude for all pulps at the same compacting pressures further confirming effects of this kind noted in earlier studies. The densities of the mats after air drying without restraint were related to the compacting pressure by straight lines on log-log plots having similar slopes but displaced along the pressure axis for densities below about 0.7 to 0.75 g./cm.^{3}. Thereafter, the lines curved toward the pressure axis with the indication that densities above 1.1 g./cm.^{3} might not be obtained even with substantially higher compacting pressures.

The relationship of elastic modulus in bending to dry mat density was of a form yielding straight lines on a log-log plot with a slope of 2.9 for the classified pulp, 2.66 for the whole pulp, and about 2.0 for the pulp with fines added. The slope was not established for the refined pulp. The effect of wet pressing on the dry mat modulus-density relationship differed for the different pulps in a significant manner. The addition of fines to whole unbeaten pulps produced important increases in the bending modulus at similar densities — an effect of apparent importance in furnish development studies aimed at maximizing bending stiffness at lowest furnish cost and highest paper machine productivity.

The z-direction tensile strengths of the various mats exhibited effects with furnish and wet pressing changes qualitatively consistent with the bending modulus behavior.

A comparison of flexural rigidities was made through use of the ratio of bending modulus to the mat density cubed. When this ratio was plotted <u>versus</u> the wet mat solid content, it was noted that the refined pulp and the pulp having 10% added fines give best results of similar magnitude. The flexural rigidities of the whole pulp were considerably lower and those of the classified pulp very much lower compared at either equivalent wet mat solid contents or dry mat densities.

The effect of adding or removal of fines is considered to be of particular importance in the analysis of the results, demonstrating rather strongly that relationships between the structure and properties of dry mats may prove difficult to establish unless the specific role of the fines can be better understood. Thus, the relationship of dry mat density in a relatively unambiguous manner to the dimensions and mechanical properties of the individual fibers will be most difficult for all but very special furnishes. Continued experimentation following and extending these initial studies would appear to be useful in further development of the subject, however.

INTRODUCTION

The density of fibrous mats has long been an important parameter in the characterization of their structure. In an early study by Doughty (1), it was shown that the tensile strength of paper prepared from never-dried pulp could be correlated well with solid fraction using all data obtained at all beating and wet pressing levels. If the pulp were dried and rewetted, it would behave similarly only after a period of beating to recover the adverse effect of drying on strength. Thus, it was felt for many years thereafter that the density of the uncalendered sheet was a basic descriptive property, which is relatively independent of the means of achieving that density; for example, through more or less beating or wet pressing. This view is popular today as well and still essentially accurate although there are now many data suggesting that sheet density is not a basic characterization of structure. Even in the early studies, however, the presence of complicating factors related to fiber dimensions, etc., was recognized.

Luner, et al. (2) reported a general correlation between sheet-density-squared and the tensile elastic modulus of paper with only minimal departures for some furnishes. Setterholm and Chilson (3) also tended to favor correlations which related sheet density to tensile strength and elastic modulus without regard for the means of achieving the particular densities. They reported, however, that a rigorous correlation between sheet density and elastic modulus was not to be expected if drying temperature was a variable. Closer examination of the data of Luner, et al., and that of Setterholm and Chilson as well indicate that the departures from the overall general correlations of density with elastic modulus are significant and not to be ignored.

Studies of the elastic properties of paper and paperboard in relationship to density are of direct interest in the development of improved bending stiffness in such products. Considerable effort has been devoted to the development of "low density" board in which the highest possible bending stiffness is desired at a given basis weight or, conversely, in which a desired stiffness is achieved at lowest possible basis weight.

The processing means wherein sheet density can be changed for a given pulp include dry calendering, wet pressing, and refining. Of these, dry calendering is clearly adverse in its effect on elastic modulus and it is quite possible to effect reductions in strength through the dry calendering process. Wet pressing and refining are certainly not similar in the mechanism by which the sheet density is increased. Refining results in swelling of the fiber and usually increases the fines content of the furnish as well. Wet pressing, on the other hand, does neither. It would be surprising, therefore, if refining and wet pressing were precisely alike in their effect on the relationship between sheet density and elastic modulus. From a more careful analysis of the effects of beating and wet pressing on the density-to-elastic-modulus relationships in the literature, it can be claimed that any general similarity in the effects of beating and wet pressing is oversimplistic and that important and useful differences do exist.

The role of fiber morphology and fiber dimensions on the density-modulus relationship is not well defined at all. It is easy enough to compare the pulps at hand, but one's ability to relate the properties and dimensions of individual fibers to sheet density remains poor.

The beneficial effect of the size press on sheet stiffness is quite well known to all working in this area, but this subject is not part of this study.

The determination of sheet density as the ratio of basis weight to sheet caliper leads to an "apparent density" value because of problems associated with the measurement of sheet caliper and because of the apparent variations in sheet density from the interior of the sheet to the surfaces. Changes in apparent density with basis weight are well illustrated by the data of Taylor (4), for example. In research studies, the inaccuracy of "apparent density" as a proper measure of sheet density is important.

Most of the published data relating apparent density to elastic modulus deal with the tensile elastic modulus obtained from the initial slopes of load-elongation curves. For sheets of uniform structure and properties (throughout the sheet thickness dimension), the tensile elastic modulus and the elastic modulus determined in beam bending should be rather similar in magnitude. The restraints provided by the Poisson effect in thin paperboard beams should lead to a bending modulus approximately 9 to 10% lower than the tensile modulus if simple beam formulae are used and no other effects are involved. If the sheet properties vary throughout the sheet thickness, the two moduli can differ in various ways. It appears that the usual differences in handsheets lead to lower bending moduli compared to those determined in in-plane tension. Malmberg (5) reports bending moduli only about 60% as large as the tensile moduli for lightweight handsheets. The differences should be considerably less for heavier paperboards and, possibly, of negligible importance for fibrous pads of very heavy basis weight. The decision to work with heavy fibrous pads in this work was made with the view that much more reliable density determinations would be possible via direct caliper measurements and that the bending modulus would be both similar in magnitude and bear similar relationships to sheet density as would the tensile modulus.

In any study of the relationship between sheet density and sheet properties, changing the density through wet pressing must play an important part. Research studies of the compaction of wet mats have been numerous over the past 20 years, but there is still an inadequate understanding of the actual mechanisms involved in compaction. Even today, it is not always appreciated that wet mats exhibiting similar if not identical compression response at the quasi-equilibrium point can differ tremendously in their actual structures when wet. Studies of the relationships between wet mat properties and dry mat properties should be a fruitful pursuit and could be quite useful toward pointing the way to a better understanding of the density-elastic modulus relationship, for example. This initial study of wet mat compression and dry mat properties was carried out with this view in mind. Its immediate value, it was hoped, would be a better appreciation of the problem of maximizing bending stiffness at constant basis weight.

EXPERIMENTAL

APPARATUS

Apparatus of the type normally used in filtration studies was modified for use in this work. The apparatus was modified so that after a mat was formed by filtration at low consistency, a piston could be applied to the top of the mat and pressing be carried out in the same sheet-forming apparatus. This apparatus is shown schematically in Fig. 1.

Pressing loads were applied using dead weights at the lower loads. For higher pressures, however, any of three different air-loaded diaphragms were used depending on the magnitude of load required. These included the Robotair Type 6, the Rotochamber Type 9, and the Rotochamber Type 50, all manufactured by the Bendix-Westinghouse Automotive Air Brake Company, Elyria, Ohio. The first two units were calibrated directly using a Toledo scale. The largest unit, the Rotochamber Type 50, was calibrated using the Baldwin-Southwark Universal Tester.

In the tests performed at low pressures, it was possible to use a Lucite cylinder and a Lucite piston. At higher pressures, however, the modified apparatus having a brass cylinder and brass piston was used. The pistons were fitted closely to the cylinder in either case. Three threaded holes of 1/8-inch dimension passed through the pistons. These were necessary to facilitate the removal of air as the piston was installed over the mat and to permit the introduction of air to the mat surface as the piston was withdrawn following compression. During compression, these holes were closed with threaded rods.

Although no changes were made to the original septum, the deflection of the supporting wire into the septum openings at the higher pressures was sufficiently large to justify the construction of a special septum in further compression

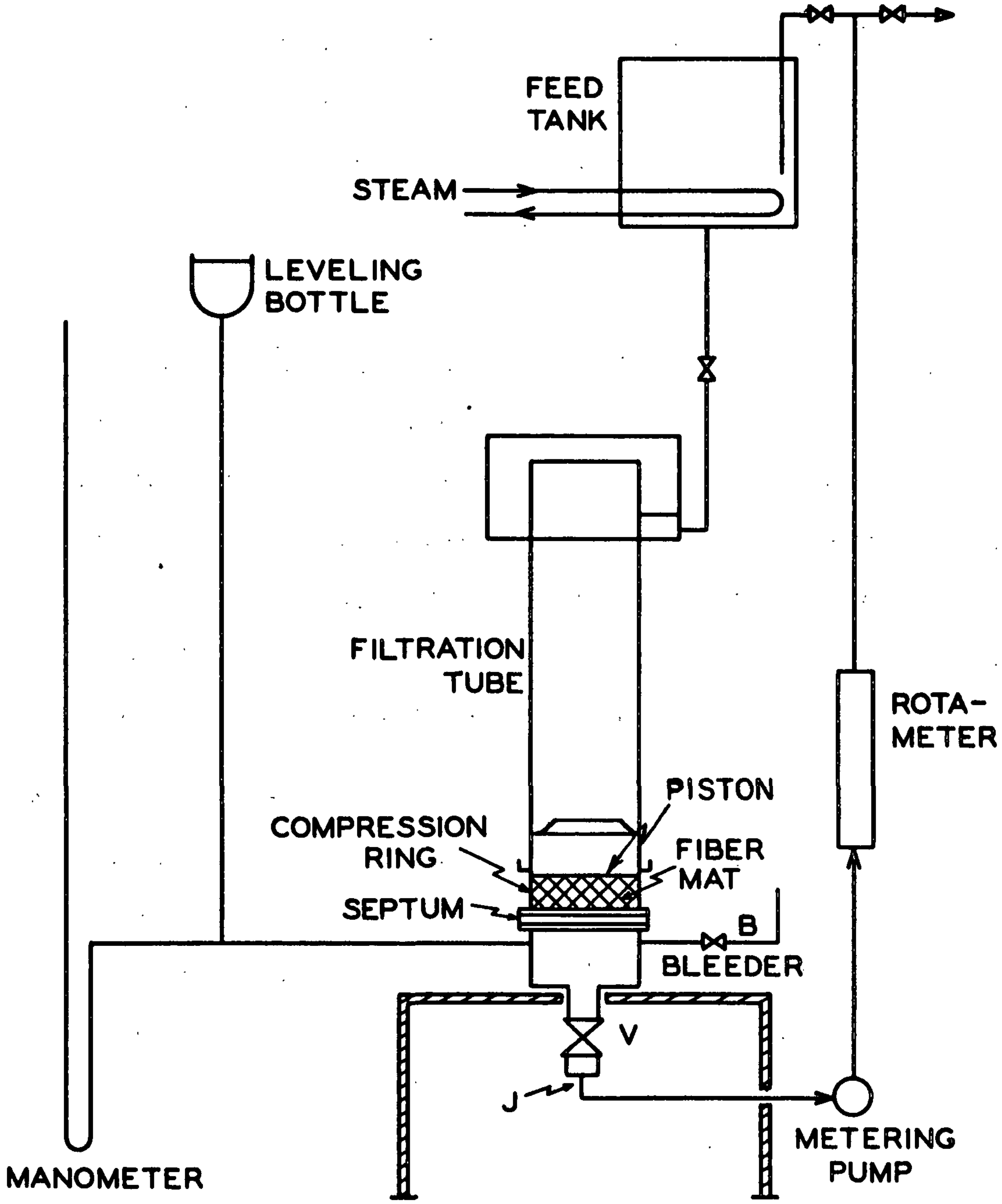

Figure 1. Schematic Diagram of Mat Forming Apparatus

studies of this kind. The septum was covered with a 150-mesh copper screen which was supported by a 35-mesh screen. Details of the cylinder, piston, and septum are shown in Fig. 2.

PULP SAMPLES

The southern pine bleached kraft pulp used in an earlier study of the pressure dependence of specific volume and surface (6) was used in this work. The dry lap was soaked in water for 24 hours and then dispersed in a British disintegrator for 10 minutes. The five different pulp samples described below were studied.

W-Series — Whole unbeaten and unclassified pulp was used in the first and most extensive series of runs. The Canadian Standard Freeness of this pulp was determined as 730 ml.

C-Series — Fifteen-gram portions of the whole pulp of the W-Series was classified in a Bauer-McNett classifier for 20 minutes using 14, 20, and 35-mesh screens. Only the material retained on the three screens was combined to form this sample. The freeness of the C-Series sample was measured as 760 ml.

1R-Series — The whole pulp was refined in a Valley beater using a 6500-g. bedplate loading to a freeness of 595 ml.

2R-Series — The whole pulp was refined in a Valley beater using a 6500-g. bedplate loading to a freeness of 445 ml.

WF-Series — The whole pulp was mixed with 10% by weight of fines obtained by Bauer-McNett classification of whole pulp and collecting the material which passed through a 60-mesh screen.

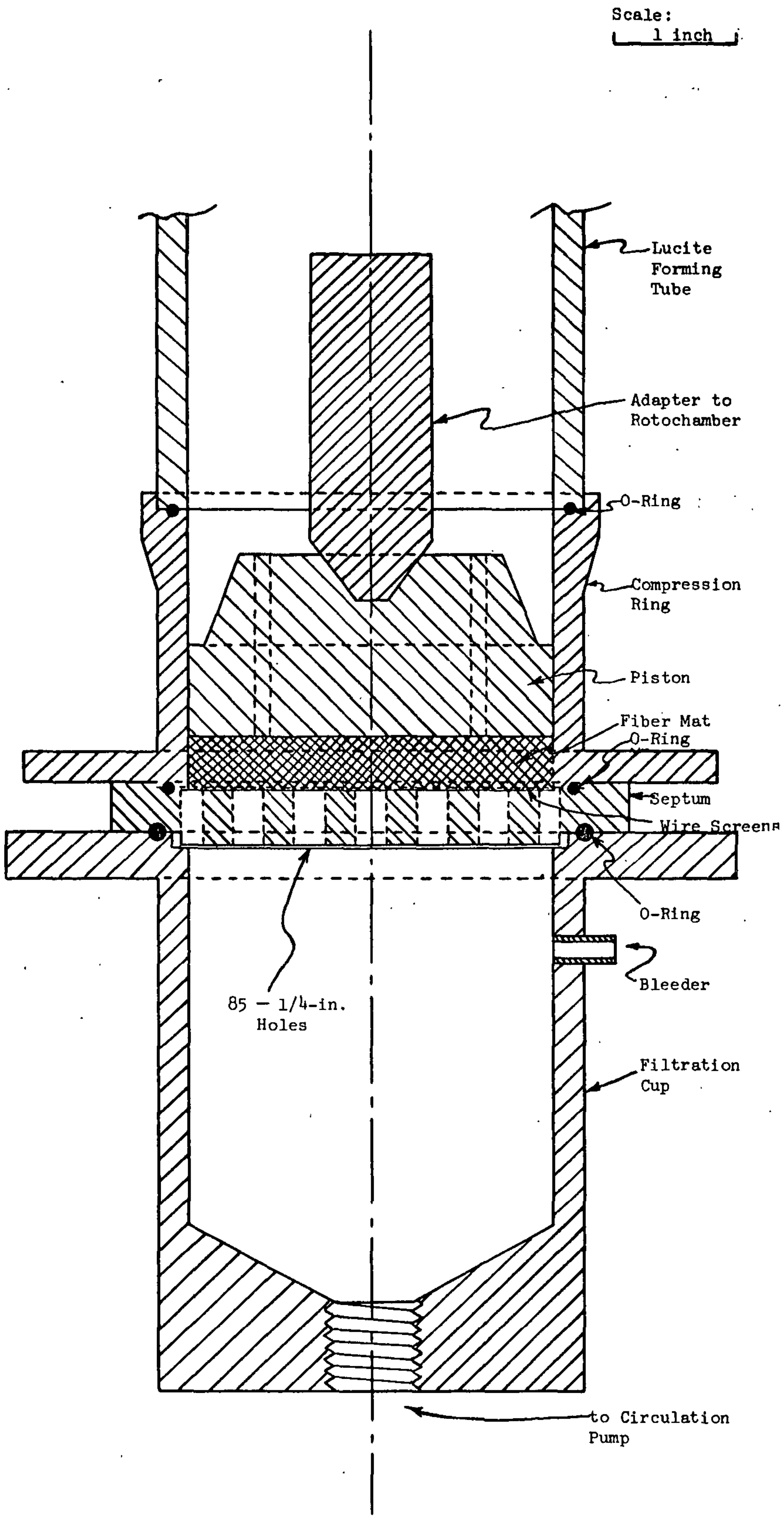

Figure 2. Piston-Compression Ring-Fiber Mat-Septum Area

WET PRESSING

At the end of the mat-forming process, particular care was taken not to allow air to enter the fiber mat. The following procedure was followed. The valve on the feed line to the filtration tube was shut off and the flow through the metering pump was reduced. When the water level dropped to about 1 inch above the surface of the mat, the flow through the pump was stopped completely. Further drainage to the point where the piston can be put in place is done slowly under the action of gravity. Air is not permitted to enter the mat.

For Runs C1-C20, W1-W5, and IR1-IR5, inclusively, the Lucite piston was used. For all other runs the brass piston and compression cylinder shown in Fig. 2 was used. The piston was laid gently onto the fiber mat. Valve V, shown in Fig. 1, was closed and the drainage piping was disconnected at Joint J. The bleeder Valve B was opened and Valve V was opened slightly to allow the water in the cup to drain very slowly. The desired pressure was then applied using the appropriate dead weight or air pressure in the diaphragm chamber. The water removed in pressing was discharged through the septum and removed through the drain line J. Fifteen minutes were allowed from the application of the pressing load until the applied load was removed. This was sufficient time for the attainment of apparent equilibrium in compacted thickness in many of the runs, particularly those involving unbeaten pulps. In the case of refined pulps at the highest pressures, the mat thickness was changing at about 0.005 cm. per five-minute interval. In all cases the recorded wet mat density was that measured at the end of 900 seconds of pressing. It is understood, of course, that all of the wet mats were undergoing continued compression in creep at the completion of the 900-second pressing period.

Examples of the mat thickness _versus_ time under load relationship for four different runs are given in Table I.

TABLE I

MAT THICKNESS VERSUS TIME

Run	Mat Thickness, cm. 1R11	1R10	C25	W10
Applied pressure, dynes/cm.^{2} x 10^{-6}	47.1	3.70	47.6	47.6
Time, sec.				
30	0.325	0.450	0.190	0.205
60	0.295	0.415	0.190	0.195
90	0.275	0.405	0.190	0.190
120	0.260	0.405	0.190	0.190
180	0.245	0.395	0.190	0.190
300	0.230	0.390	0.185	0.190
450	0.220	0.390	0.185	0.190
600	0.215	0.385	0.185	0.190
900	0.210	0.385	0.185	0.190
1200	0.205	0.385	0.185	0.190
1500	0.200	0.385	0.185	0.190
1800	0.195	0.385	0.185	0.190

When the applied load is reduced and eventually removed, the mat expands and some of the water held in the septum can be reabsorbed by the mat. This rewetting is always present in commercial wet pressing, but it was hoped to minimize rewetting in this experimental work. It could not obviously be eliminated using the experimental approach described here. To determine the amount of water reabsorbed, a set of 9 tests was made in which the septum was carefully wetted with water followed by applying blotters of known total weight to the septum. Loads of different magnitude were then applied to the blotter and septum followed by unloading and removal and weighing of the blotters. The results shown in Table II indicate that the amount of reabsorbed water was unaffected by the magnitude of the applied load and was relatively constant in the various tests at about 2.95 g.

When the Type 50 Rotochamber was used at the highest applied loads, the wire screen was deformed permanently into the septum support and the amount of water reabsorbed measured by the same technique varied considerably. Further tests were then directed toward reducing the amount of reabsorbed water. An air jet was introduced through the opening at Point J and brushed over the underside of the septum to remove the pendant water at that point. After recovering of the septum with new wires, the extent of reabsorbed water was again determined with the results shown in Table III.

TABLE II

WATER REABSORBED BY BLOTTERS

Applied Pressure, dynes/cm.^{2} x 10^{-6}	Water Reabsorbed, g.
0.268	2.91
0.268	2.98
0.268	2.98
1.65	2.97
1.65	2.95
2.93	3.07
4.14	2.74
5.31	2.90
5.83	2.95

TABLE III

WATER REABSORBED AFTER PENDANT WATER REMOVAL

Applied Pressure, dynes/cm.^{2} x 10^{-6}	Water Reabsorbed, g.
3.70	2.00
13.5	2.14
23.2	1.96
33.3	1.88
48.1	1.92

Although there appeared to be slightly greater variability using air-jet brushing of the septum bottom, the amount of reabsorbed water was reduced. If an average value of septum rewet of 2 g. is assumed, the maximum error in this assumed value might be no greater than about 0.15 g. The addition of 2 g.

of water would cause a reduction in the solid content value from 30 to 28.1%, from 60 to 52.8%, and from 70 to 60.8% (8.8 g. dry fiber). The small clearance between the piston and the filtration tube or cylinder wall was also filled with water during pressing. This water is available for absorption by the mat when it expands. The amount of water available from this source was calculated as 0.15 g. The actual experimental data are largely consistent with a total sheet rewet of 2.15 g.

It was originally hoped that the mats could be dried in the drainage apparatus by drawing air through the mats. This proved to be most difficult. In some cases, the permeation of the mats was simply too low to permit reasonable drying rates and, in those cases where the mats could be dried, serious distortion occurred, due probably to nonuniform drying. Thus, the mats were removed from the filtration and pressing apparatus, weighed, then dried at 50% R.H. and 73°F. without any applied restraint. The application of restraint was judged to be impractical for mats of these dimensions.

Five mats were oven dried to constant weight providing the data shown in Table IV.

TABLE IV

CONTROL-ROOM-DRIED AND OVEN-DRIED MAT WEIGHTS

Run No.	Control-Room-Dried Mat Weight, m_c, g.	Oven-Dried Mat Weight, m_f, g.	Ratio, m_f/m_c
C14	9.4079	8.6873	0.9234
C16	8.6366	7.9555	0.9211
W2	9.6141	8.8568	0.9212
1R2	10.2980	9.4724	0.9198
1R10	9.5447	8.7949	0.9214
		Average:	0.9214

The average of all five values was used in calculating the ovendry weights for all of the remaining mats.

z-TENSILE TESTING

The z-direction tensile strengths of the dry mats were determined at 50% R.H. and 73°F. using a table-model Instron. The procedures described by Wink and Van Eperen (7) were followed with the modification that 3/4 x 3/4-in. square specimens were tested rather than the circular specimen normally used in such tests. This change was made to facilitate preparation of the specimens for testing with minimum stress in the cutting.

BENDING MODULUS DETERMINATION

Determinations of the modulus of elasticity in beam bending were made using specimens between 0.5 and 0.68 in. in width. The beam thicknesses were lower than the mat thicknesses after air drying. Both surfaces of the mats were removed by lightly abrading the specimens on flat plates covered with fine sandpaper. Thus, the specimens tested were taken from the central part of the mats. It was felt that the mat structure was not disturbed as a result of the mild abrading action used to shape the beam specimens.

The specimens were tested as simple end-supported beams with central loading using 1/4-in. diameter metal rods for both the loading and supporting anvils. The end supports were 2.25 in. apart. Deflection was performed using the Instron tester and the maximum central deflection of 0.05 in. was used as the point of load determination in all tests. These data were obtained at 50% R.H. and 73°F.

The moments of inertia of the specimens were calculated according to Equation (1),

$$I = \frac{b\ h^3}{12} \tag{1}$$

where

I = moment of inertia

b = specimen width

h = specimen thickness

The modulus of elasticity was calculated from the simple beam formula,

$$y_{max} = \frac{P\ L^3}{48\ E\ I} \qquad (2)$$

where

y_{max} = maximum deformation at beam center

P = applied load at y_{max}

L = beam length

E = modulus of elasticity

RESULTS AND DISCUSSION

WET MAT DENSITIES

The densities of the compacted wet mats after 900 seconds of load application were shown to be changing very slowly with time (Table I), with little change occurring at this point for the unrefined and classified pulps and somewhat greater changes noted for refined pulps. In all cases, however, the wet mat is either at or has closely approached a quasi-equilibrium density. The range of compacting pressures used was 0.044 to 48.12 millions of dynes/cm.^{2} (0.638 to 698 p.s.i.). All of the wet mat density versus applied pressure data are plotted on a log-log basis in Fig. 3 and summarized in Table V. It is noted that all data fit a single curve quite well. This type of behavior was noted in the earliest work by Ingmanson (8) and was established more firmly in a study of the effect of refining on the properties of wet pulp mats by Ingmanson and Andrews (9). One must emphasize that the similar wet mat densities exist at similar applied compacting pressures for pulps beaten to different degrees, pulps classified by the removal of fines and pulps to which fines have been added (at quasi-equilibrium). In dynamic pressing to similar short pressing times, this may not be the appropriate conclusion. The more highly swollen pulps and the unrefined pulps may not be pressed to similar wet mat densities in short pressing times.

The similarity in wet mat compaction for the different pulps has not received sufficient attention in relating the structure of the dry paper to the structure of wet mats. There is unfortunately no way to characterize wet mat structure directly at present, particularly in the important aspect of the extent of interfiber contact in wet mats. It is rather obvious that although similar wet mat densities are achieved at similar pressures for beaten and unbeaten pulps,

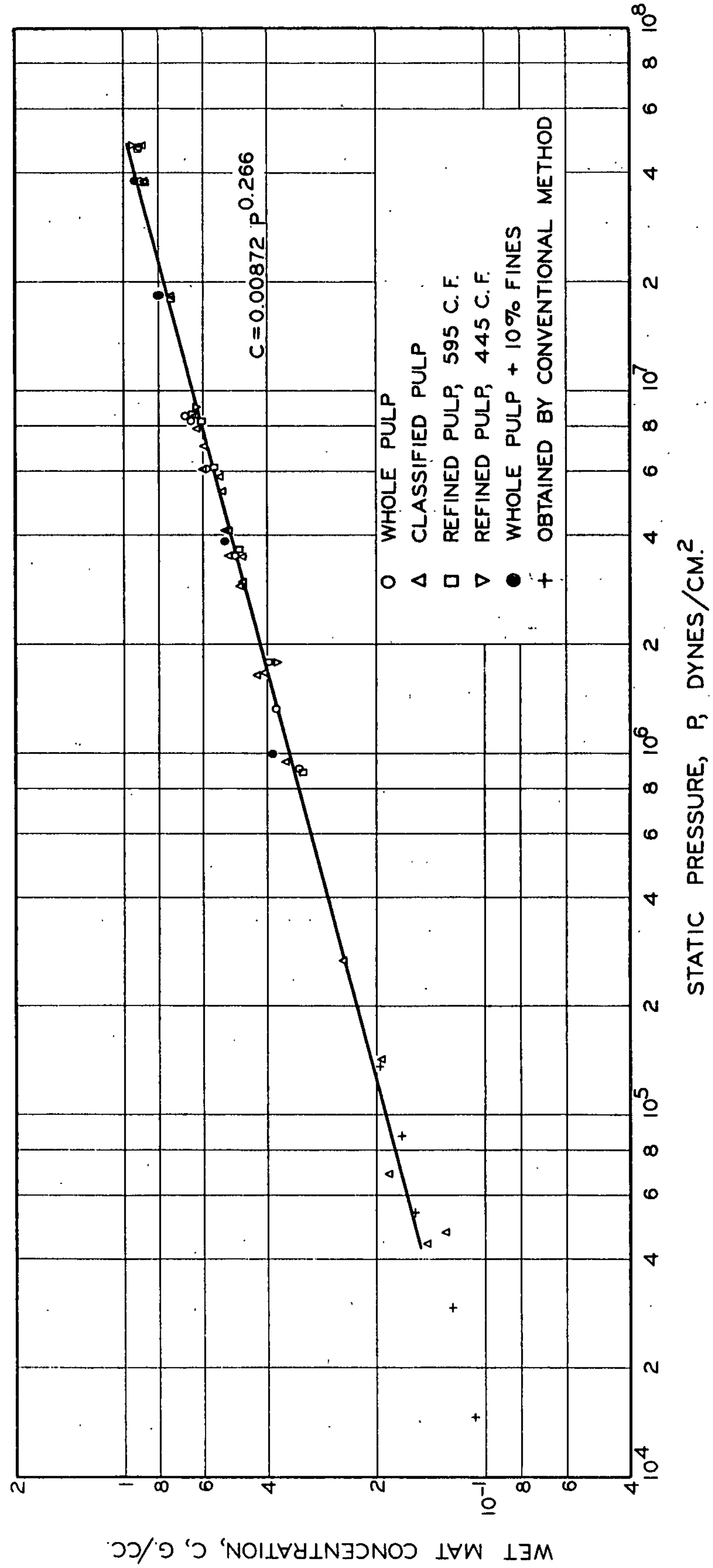

Figure 3. Wet-Mat Density *Versus* Pressure Applied to Wet Mat

TABLE V

SUMMARY OF WET AND DRY MAT DATA

Run No.	Temp., °C.	Compacting Pressure, dyne/cm.^{2} x 10^{-6}	Compacted Wet Mat Thickness, cm.	Compacted Wet Mat Density, g./cm.^{3}	Dry Mat Weight, o.d., g.	Dry Mat Thickness, cm.	Dry Mat Density, g./cm.^{3}	Actual Wet Mat Solid Content, %	Compacted Wet Mat Solid Content, %
W1	23.8	0.903	0.605	0.323	8.88	0.536	0.386	26.1	29.0
W2	24.1	1.334	0.515	0.378	8.85	0.476	0.433	29.8	33.4
W3	24.5	3.526	0.390	0.491	8.71	0.372	0.546	36.9	41.9
W4	24.5	6.158	0.330	0.587	8.80	0.336	0.609	40.6	48.6
W5	24.8	8.376	0.300	0.643	8.77	0.316	0.644	42.5	52.4
W6	25.5	8.588	0.286[a]	0.677	8.82	0.316	0.643	47.0	54.7
W7	25.5	18.47	0.244[a]	0.793	8.79	0.274	0.735	50.4	61.9
W8	25.9	38.25	0.217[a]	0.893	8.80	0.235	0.858	58.5	67.9
W9	25.9	48.12	0.209[a]	0.927	8.80	0.231	0.872	59.7	69.8
W10	25.1	47.62	0.211[a]	0.907	8.70	0.240	0.835	57.6	68.7
C1	27.3	0.044	1.21	0.148	7.95	1.06	0.178	13.3	13.8
C2	28.9	0.047	1.48	0.151	8.62	1.30	0.156	12.2	12.3
C3	28.0	0.069	0.945	0.167	7.88	0.919	0.197	16.1	17.3
C4	28.7	0.142	0.910	0.203	8.01	0.860	0.218	18.2	18.2
C5	22.3	0.268	0.790	0.241	8.82	0.826	0.247	21.2	22.6
C6	29.0	0.953	0.525	0.339	8.42	0.603	0.320	28.2	31.4
C7	24.9	1.647	0.455	0.393	8.74	0.571	0.351	30.8	36.8
C8	25.1	1.677	0.480	0.395	8.88	0.549	0.371	31.8	35.6
C9	24.1	2.929	0.410	0.459	8.76	0.503	0.398	34.7	40.3
C10	26.2	2.958	0.400	0.460	8.40	0.461	0.417	34.3	39.7
C11	26.1	3.535	0.360	0.482	8.29	0.459	0.413	34.3	43.0
C12	21.8	4.141	0.380	0.503	8.90	0.464	0.438	36.6	43.6
C13	27.1	4.141	0.375	0.503	8.80	0.446	0.451	36.4	43.7
C14	27.5	5.305	0.360	0.538	8.66	0.422	0.470	37.7	44.6
C15	24.8	5.833	0.340	0.552	8.30	0.393	0.481	38.0	45.2
C16	28.2	3.517	0.375	0.482	7.96	0.390	0.468	35.7	40.1
C17	24.9	6.158	0.311	0.560	8.40	0.375	0.513	39.2	49.1
C18	26.1	7.100	0.315	0.582	8.51	0.372	0.523	40.1	49.1
C19	23.8	7.936	0.300	0.600	8.49	0.368	0.526	40.9	51.0
C20	27.2	8.799	0.290	0.616	8.38	0.354	0.541	41.6	51.9
C21	24.1	8.70	0.296[a]	0.615	8.47	0.367	0.526	46.6	51.5
C22	24.8	18.47	0.257[a]	0.753	8.57	0.304	0.640	52.8	58.3
C23	25.1	38.25	0.213[a]	0.915	8.50	0.255	0.754	58.4	67.0
C24	24.9	48.12	0.210[a]	0.974	8.49	0.251	0.765	58.8	67.7
C25	24.2	47.62	0.207[a]	0.971	8.55	0.271	0.719	54.4	68.7
1R1	24.8	0.894	0.590	0.329	8.50	0.361	0.582	25.0	28.5
1R2	23.4	1.792	0.530	0.395	9.48	0.344	0.679	30.5	34.6
1R3	22.8	3.544	0.405	0.473	8.71	0.280	0.759	34.9	40.5
1R4	23.2	6.193	0.345	0.549	8.78	0.259	0.825	39.8	46.8
1R5	23.1	8.376	0.320	0.594	8.76	0.247	0.864	41.8	49.7
1R6	24.1	8.696	0.298[a]	0.600	8.62	0.236	0.882	47.1	51.9
1R7	24.6	18.37	0.264[a]	0.731	8.82	0.223	0.952	51.9	58.2
1R8	24.6	38.25	0.225[a]	0.887	8.90	0.208	1.019	58.3	66.5
1R9	24.7	48.12	0.207[a]	0.942	8.81	0.205	1.019	59.8	70.4
1R10	25.5	3.698	0.402[a]	0.479	8.79	0.285	0.754	38.8	41.2
1R11	26.1	47.13	0.210[a]	0.937	8.69	0.209	0.996	58.0	68.8
2R1	24.3	1.792	0.511[a]	0.383	8.71	0.3105	0.700	30.9	33.1
2R2	26.8	9.028	0.234[a]	0.602	6.69	0.1858	0.884	45.6	51.4
2R3	23.3	48.12	0.204[a]	0.962	8.74	0.2044	1.037	59.2	70.7
WF1	22.5	3.869	0.340	0.534	8.09	0.308	0.615	40.5	44.2
WF2	23.8	18.47	0.220	0.785	7.95	0.233	0.797	51.4	62.1
WF3	24.7	1.008	0.450	0.383	7.92	0.394	0.474	31.5	34.1
WF4	22.9	38.17	0.188[a]	0.940	8.02	0.215	0.864	55.5	70.4

[a]Adjusted for the deformation of the cover screen of the septum.

the wet interfiber contact area must be considerably increased in wet mats as a result of beating. The mechanism by which this comes about may be due in part to an increase in fiber volume followed by a localized distributed deswelling of the fiber of substantial magnitude in areas of high local pressures and appreciably less in regions of low local pressures. Thus, nonuniform deswelling of swollen fiber might be viewed as an important effect in developing increased interfiber contact area in wet mats prepared from beaten pulps.

DRY MAT DENSITIES

The densities of the mats after drying to equilibrium at 50% R.H. and 73°F. without restraint of shrinkage are plotted versus the pressure applied in wet mat compaction on a log-log basis in Fig. 4. A family of curves is obtained for the different pulps which appear to be quite similar in shape but shifted along the pressure axis. For dry densities below about 0.7 or 0.75, the slopes of the various lines are very nearly identical at about 0.218 compared to a slope of 0.266 for the wet mats. At higher dry mat densities, the lines curve toward the pressure axis and do not show promise of exceeding densities of about 1.1 $g./cm.^3$ even at substantially higher wet pressures. The curvature appears to be gradual. No abrupt change could be claimed from a study of these data. For the classified pulp, no curvature is noted within the pressure range used. It may be of interest to note that MacLaurin and Whalen (10) show maximum apparent densities of only about 0.7 $g./cm.^3$ in pressing experiments on lightweight papers prepared from Douglas-fir kraft pulps. Such lower limits in their work could well be attributed to the lower pressures used, to dynamic pressing, etc.

Shifting of the various curves of Fig. 4 along the pressure axis would appear to bring them into reasonable coincidence. Thus, a classified pulp responds

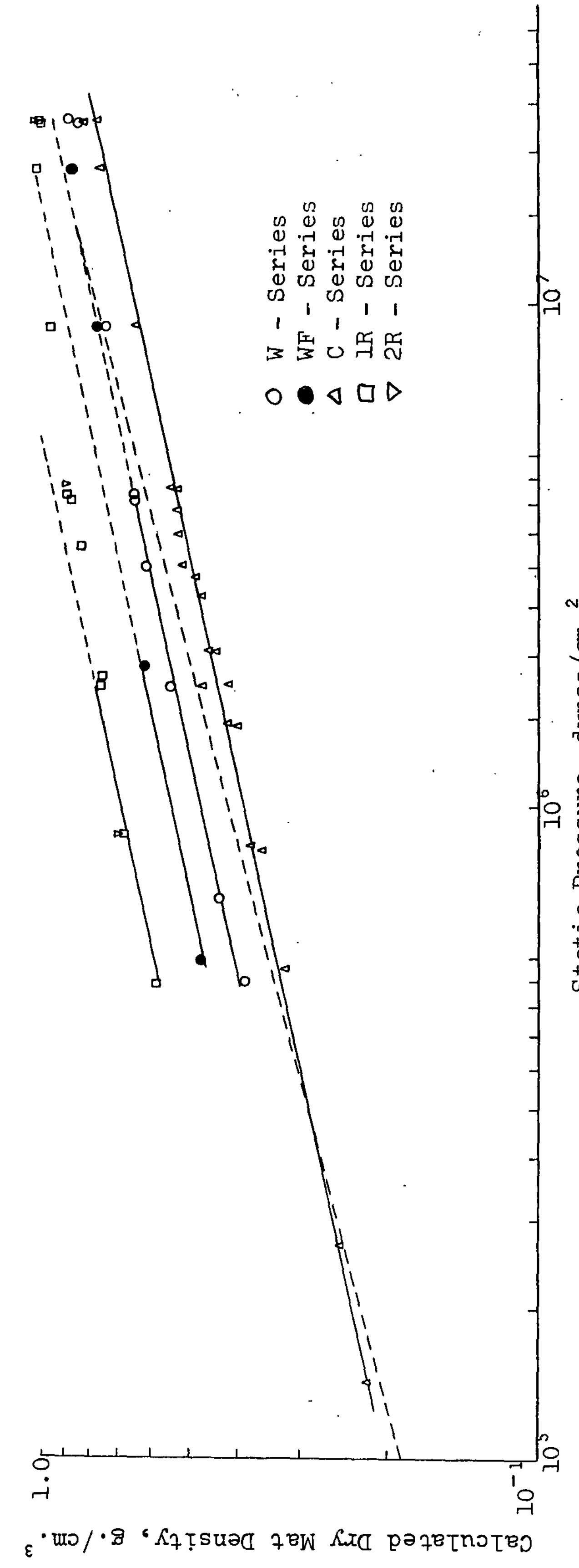

Figure 4. Dry-Mat Density <u>Versus</u> Pressure Applied to Wet Mat

similarly to wet pressing in the determination of dry mat density except that pressures about 14 times greater are needed to develop a dry density of, say, 0.6 g./cm.^{3}, than is required for the refined pulps. This is a most substantial difference when one notes further that the corresponding compacted wet mat density for the refined pulp is only half that of the classified pulp. In an attempt at an explanation, one would certainly look toward mechanisms involving fiber collapse, interfiber contact area effects, fiber bending and fiber axial tension forces.

It would have been instructive at this point to have had data of the dimensions of the wet mats after the wet mat compacting loads were removed. Unfortunately, these data were not obtained. Seborg, et al. (11), in the early 1930's, attempted to develop a method of pulp evaluation which was based on the extent of springback or the recovery of deformation of wet compacted mats. They noted that for a wide variety of pulps, the springback was greatest for unrefined pulps and often quite low for refined pulps (only 6 to 10% recovery in thickness, for example). It would be easy in the absence of pertinent data to assume that these differences in dry mat density are attributable mainly to differences in springback. It is doubtful, however, that the situation is that simple, and further speculation is ill advised at this point. Experimentation in which springback data were included would be most interesting, obviously.

WET MAT SOLID CONTENT

The amount of water carried into the drier section of a paper machine with the wet mat often directly determines the machine speed and always affects the drying cost. This can be a particularly vexing problem in the production of low-density board where it is desirable to reduce the amount of wet pressing below that which is normally practical. It is of interest, therefore, to examine the wet mat solid content after pressing for the various pulps and ultimately its relation to the dry sheet properties.

The solid content, S, of a wet mat in a fully-saturated state expressed as a weight fraction is related to the measured wet mat density, c, expressed as the weight of dry fiber per unit volume of wet mat through a simple material balance.

$$S = \frac{1}{1 - \rho_w/\rho_f + \rho_w/c} \tag{3}$$

At an assumed fiber density, ρ_f, of 1.55 g./cm.^{3} and water density, ρ_w, of 1.0, the relationship shown below applies.

$$S = \frac{c}{1 + 0.355c} \tag{4}$$

The solid content existing at the point of maximum wet mat compaction can, therefore, be calculated and if the mat could expand without the absorption of additional water, the calculated and measured final solid content of the wet mat would be the same. Only air would enter the expanding mat in this case. It is not possible to avoid some water absorption (rewetting) even in laboratory experiments of this kind. It is now generally accepted that wet mats are compacted to much higher solid content in the nip of felted commercial presses than are determined in the wet samples taken after the pressing operation. Water is drawn into the expanding mat to a substantial extent upon removal of the pressing load. The effect of the rewetting on sheet properties such as density and elastic modulus is itself of considerable interest, but it was the particular desire in this work to avoid rewetting as far as possible. The actual solid contents and the calculated solid contents in the compacted mat are given in Table V. The differences are due mainly to rewetting and show agreement with the extent of rewetting estimated in earlier experiments and presented in Table III. One notes that rewetting causes reductions in solid content of up to 15% with the greatest differences, of course, occurring at the higher solid content values. These are appreciable effects, but much smaller than the rewetting which may occur in commercial felted presses (12).

A comparison of the wet mat solid contents with dry mat densities shown in Table V illustrates the problem of obtaining low dry densities with refined pulps. The solid contents must be very low. For example, at a dry sheet density of 0.6 $g./cm.^3$, the wet mat solids content would be only about 0.25, a value which is achieved with very little wet pressing.

The dry densities of the mats are plotted _versus_ the actual measured solid contents in Fig. 5. A rather similar set of curves is obtained if the dry density is plotted _versus_ calculated solid content at maximum wet mat compaction. These data are particularly interesting when reviewed in the light of other wet pressing data reported in the literature. MacLaurin and Whalen (10), for example, noted little change in apparent density for lightweight papers (40 lb. — 24 x 36 — 500 basis) when the solid contents exceeded about 55%. It is doubtful that data obtained using different wet pressing means should be compared directly unless some knowledge of the magnitude of rewetting and some understanding of the effect of rewetting on sheet properties is available. Changes in wet mat solid content obtained by the removal of water by capillary action as may exist in the wet pressing of handsheets in the laboratory using blotters may further complicate these data.

Further discussion of wet mat solid content is deferred until the dry mat properties of bending modulus and z-direction tensile strength have been examined. The objective, of course, is to maximize the elastic modulus at a given density while maintaining the highest possible wet mat solid content.

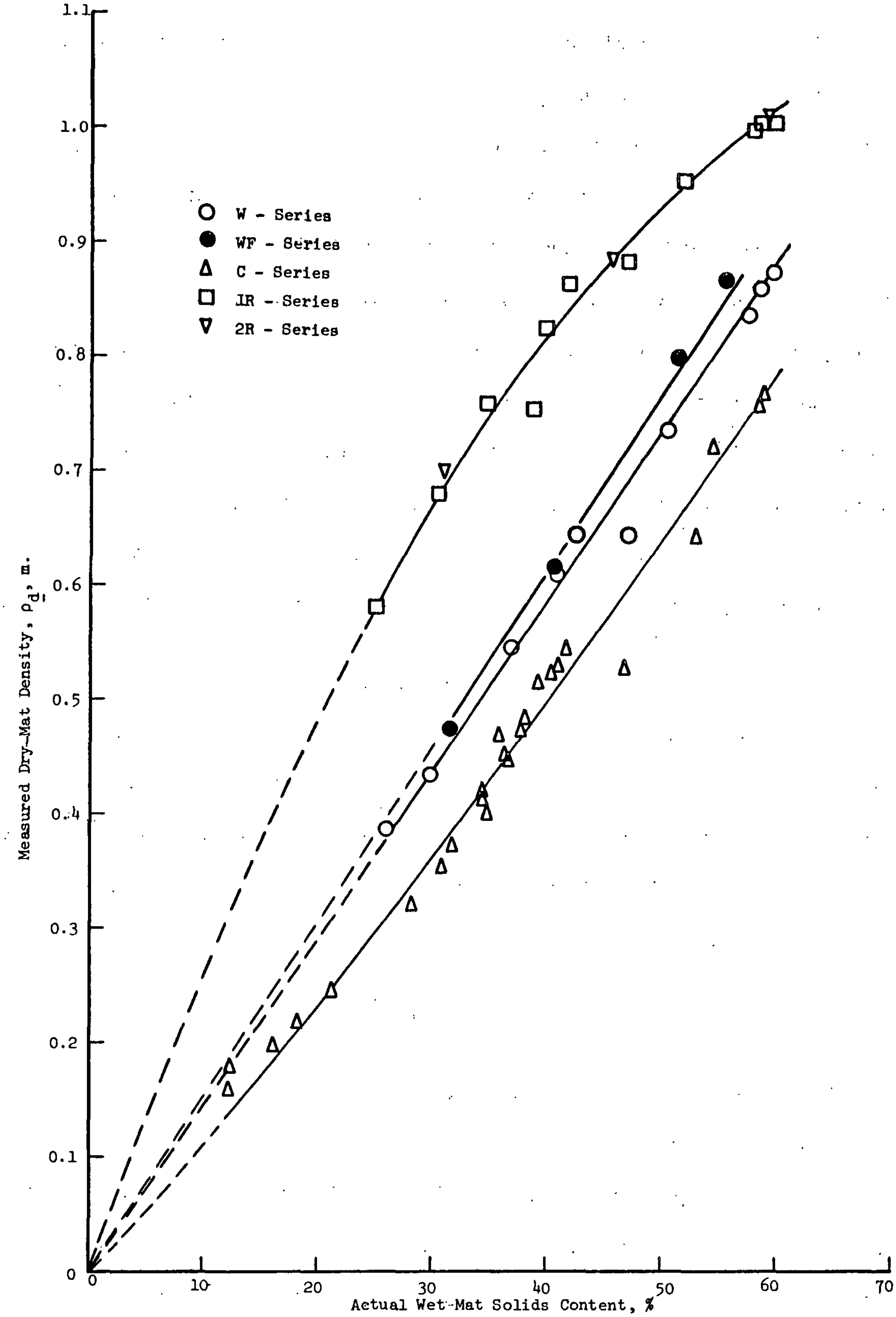

Figure 5. Dry-Mat Density Versus Wet-Mat Solid Content

ELASTIC MODULUS VERSUS DENSITY

The elastic moduli calculated from simple theory for centrally loaded end-supported beams is plotted versus sheet density in Fig. 6. These data are presented in Table VI. A very pronounced reduction in the elastic modulus at given density occurred with classification of the whole pulp through removal of a fines fraction. Modulus values only about a third of those obtained for the whole unclassified (unbeaten pulps) were obtained. The addition of fines to the whole pulp resulted in an increase in the modulus which was greater percentage-wise at lower densities (about 85% greater at a density of 0.5 g./cm.^{3}). Refining of the pulp provided for still greater elastic moduli at given density values although these data were too few and variable to give totally reliable estimates of the effect of refining. Refining appears, however, to more than double the elastic modulus of unrefined whole pulp in these mats dried without restraint.

The three pulps which were not refined all yielded straight lines on the log-log plots of Fig. 6 within experimental error. A slope of 2.93 was obtained for the classified pulp, a slope of 2.66 for the whole pulp, and a slope of about 2.0 for the pulp containing added fines. Perhaps this latter slope is also a fair approximation of that existing for refined pulps. The slope, a, is the exponent of density, ρ, in the power law relationship shown below,

$$E = B\,\rho^{a} \qquad (5)$$

where E is the elastic modulus based on the actual cross-sectional area and B is a constant, different for each furnish. If the value of the exponent a is 3, the flexural rigidity (the product of the elastic modulus and the moment of inertia of the beam cross section) is constant at constant basis weight. Thus, with a slope of 3, changes in dry mat density could be made by wet pressing

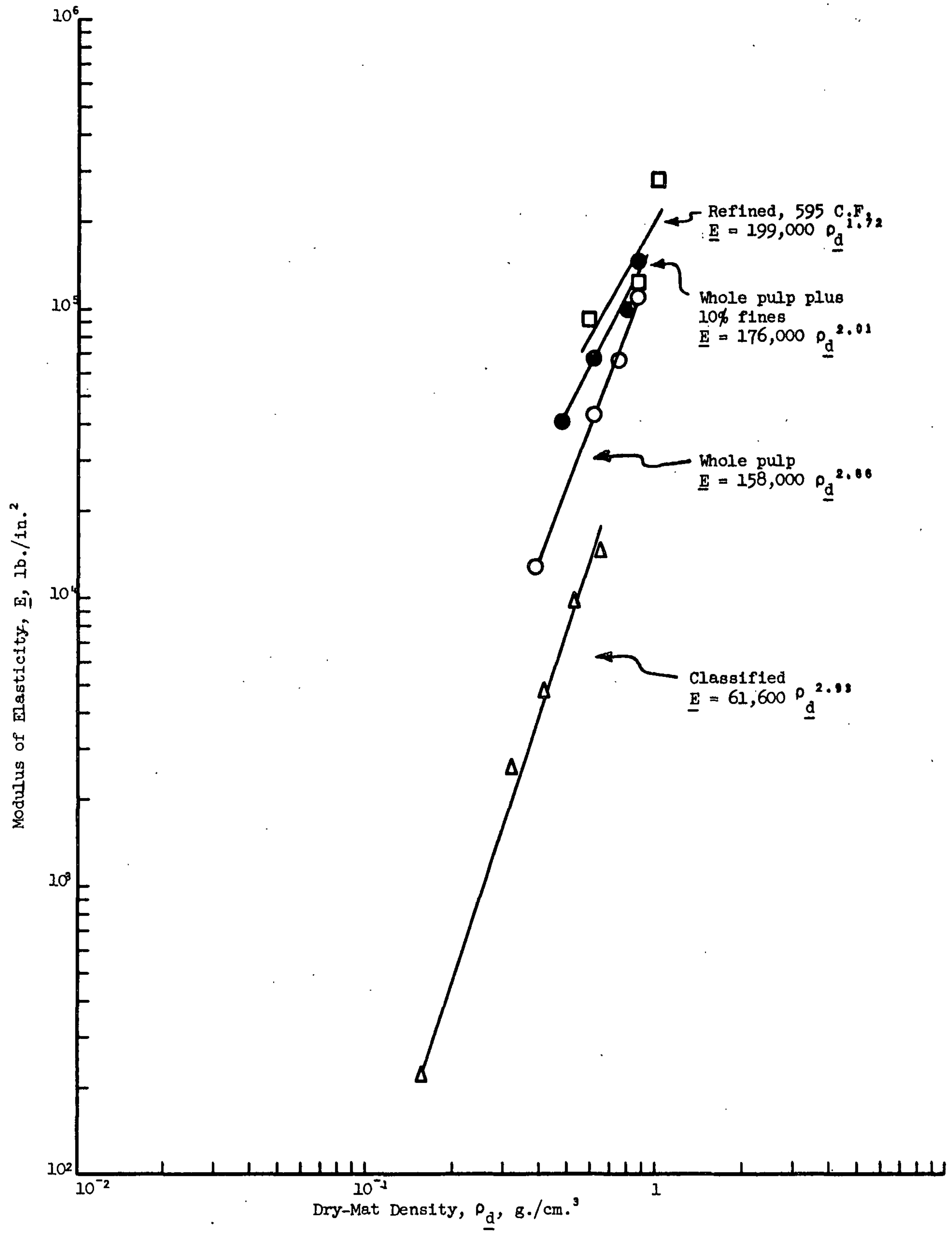

Figure 6. Bending Modulus *Versus* Dry-Mat Density

TABLE VI

ELASTIC MODULUS AND z-DIRECTION TENSILE STRENGTHS

Run No.	Beam Width, in.	Beam Thickness, in.	Load,[a] lb.	Modulus of Elasticity, p.s.i. x 10^{-4}	z-Direction Tensile Strength, p.s.i.	Dry Mat Density, g./cm.^{3}	$\underline{E}/\rho^3$, (in.^{7}/lb.^{2})10^{-9}
W1	0.655	0.220	1.55	1.27	3.9	0.386	4.68
W4	0.651	0.135	1.20	4.27	7.1	0.609	4.01
W7	0.681	0.113	1.14	6.64	23.4	0.735	3.54
W8	0.619	0.0934	0.96	10.86	25.3	0.858	3.64
C2	0.691	0.521	0.38	0.022	0.3	0.156	1.24
					0.3[b]		1.24
C6	0.633	0.229	0.35	0.26	1.4	0.319	1.72
C11	0.649	0.169	0.26	0.47	3.8	0.413	1.41
					2.4[b]		1.41
C18	0.641	0.155	0.40	0.96	3.0	0.523	1.41
C22	0.611	0.126	0.31	1.45	8.2	0.640	1.17
					11.2[b]		1.17
1R1	0.497	0.140	2.14	9.03	48.0	0.582	9.70
1R5	0.516	0.0918	1.20	12.12	62.4	0.864	3.98
					112.0[b]		3.98
1R8	0.519	0.0790	1.30	28.82	136.9	1.019	5.78
WF1	0.643	0.0917	0.86	6.64	30.3	0.615	6.05
WF2	0.631	0.151	1.52	9.89	68.4	0.797	4.15
WF3	0.638	0.122	1.34	3.99	42.8	0.474	7.94
WF4	0.634	0.0822	0.90	14.55	34.8	0.865	4.77

[a]Measured at central deflection of 0.05 in.

[b]Duplicate test.

without changing the flexural rigidity (e.g., stiffness) at constant basis weight. This is very nearly achieved with the classified pulp, but not with the other pulps.

Where the slopes are less than 3, increasing the density by wet pressing reduces the flexural rigidity expressed per unit specimen width, EI/w, as follows:

$$\frac{EI}{w} = \frac{B\ W^3}{\rho^{3-a}} \qquad (6)$$

where W is the basis weight in appropriate units. If the value of exponent a is 2, the flexural rigidity per unit width is inversely proportional to density. If the value is only 1, as might be expected in the ideal case for dry calendering, the flexural rigidity or stiffness would be inversely proportional to the square of the density. It is clear from these data that the effect of wet pressing on stiffness should not be considered in terms of some general relationship applicable for all pulps. The effect will depend on the fines content, the extent of refining, etc., of the furnish.

An exponent approaching 3 is only of special interest, however. It indicates the possibility of wet pressing the wet mat as desired to increase the solid content without reducing bending stiffness. More important, however, is the shift of the curves upward on the elastic modulus axis with the greatest shift being most desirable at the lowest densities. If, in addition, the wet mat solid content could be maximized, an approach in furnish design might be indicated. The pulp with fines added has a wet pressing curve with an exponent of only 2. Thus, wet pressing this pulp to higher density has an adverse effect on stiffness approximately inversely related to the increasing density. However, the line of lower slope, if extendable to lower densities, also means that enhanced stiffness is obtainable at the lower densities.

FLEXURAL RIGIDITY VERSUS WET MAT SOLID CONTENT

The flexural rigidity per unit specimen width is related directly to the ratio of the elastic modulus, E, divided by the density cubed where the basis weight is constant. This value is directly proportional to bending stiffness and can be used in that sense in further analyses of these data. One additional manner of treating these data is to relate the E/ρ^3 ratio to the wet mat solid content. This has been done in the log-log plot of Fig. 7. The numerical values are given in Table VI. When plotted in this way, the pulp with fines added and the refined pulps fall on essentially the same curve. No definitive conclusion about this is possible with these few data, but if such a tentative conclusion were accurate, there is no advantage from the sheet solid content standpoint in developing a furnish through the addition of 10% fines compared to refining. Though the elastic modulus at equivalent density is higher for the refined pulps, the wet mat solid contents are lower. The result is rather similar flexural rigidities at similar wet mat solid contents.

The unrefined whole pulp is poor and the classified pulp is extremely poor in flexural rigidity compared at any density or wet mat solid content.

Perhaps the point of greatest interest is that the effect of fines alone without any mechanical refining at all can have so large an effect on the elastic modulus of these fibrous structures. The addition of fines at the 10% level was purely arbitrary. Also, the fines were composed of the natural material present in unrefined pulp. Further, this pulp was once dried prior to its use in this study. Questions arise of whether an increased amount of fines would provide a still better structure from the flexural rigidity standpoint, of whether an optimum composition of fines exists and of how the sheet structure is modified by

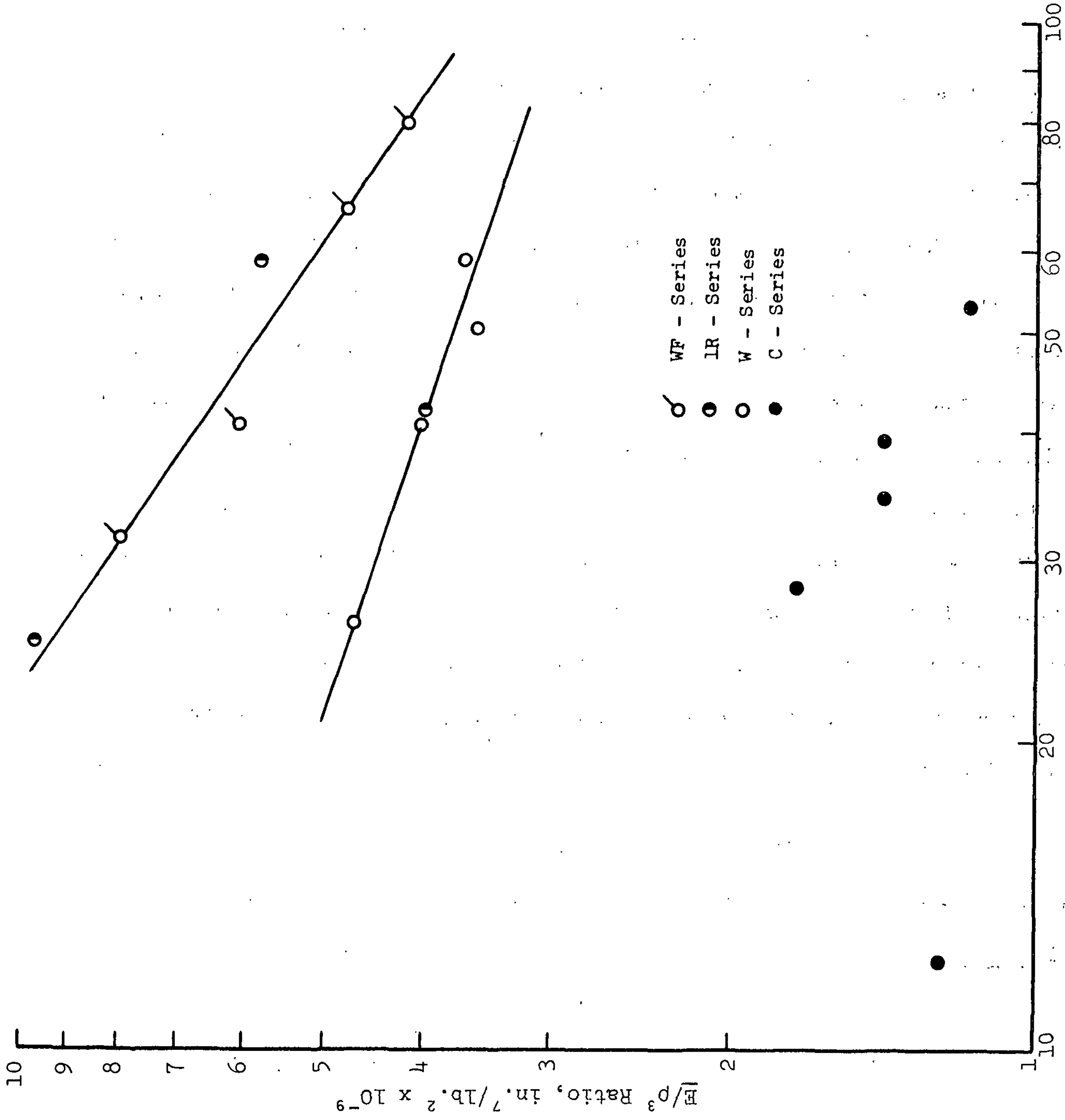

Figure 7. Ratio of Bending Modulus to the Cube of Dry-Mat Density Versus Wet-Mat Solid Content

the addition of fines compared to refining in which swelling of individual fibers is also involved.

IN-PLANE SHRINKAGE DURING DRYING

It was stated earlier that fiber mats of the thickness and diameter formed for the purposes of this study could not be gripped along the edges or otherwise restrained during drying in any satisfactory manner. Thus, it was decided to conduct the experimental work with mats dried without any restraint of shrinkage. From a review of the work of Setterholm and Chilson (3), in which pulps, refined to different levels, were dried with various degrees of restraint, it appears as if the major effect of restraint is in changing the magnitude of the elastic modulus; i.e., shifting of the elastic modulus versus density curves along the modulus axis in a log-log plot. It appeared that the slopes of the curves they obtained for various constant restraint levels were quite similar. Their data, however, were often quite erratic and do not enable firm conclusions to be drawn. Nonetheless, as a first approximation, one may assume that if in this study restraint of shrinkage were practiced, the elastic modulus-density relationships would be quite similar to those actually determined, but that the absolute value of the elastic moduli and flexural rigidities would be much higher.

It was possible to measure the diameter of the dry mats with considerable accuracy using a micrometer. The average diameters of the dry mats are plotted versus the dry mat densities in Fig. 8. These data are not summarized in the report. The forming cylinder diameter of 7.61 cm. probably does not correspond to the diameter of the wet mat after compaction. The dry mat diameters may be determined by contraction during wet mat compression and shrinkage during drying. The expected effect of increased shrinkage with refining is noted.

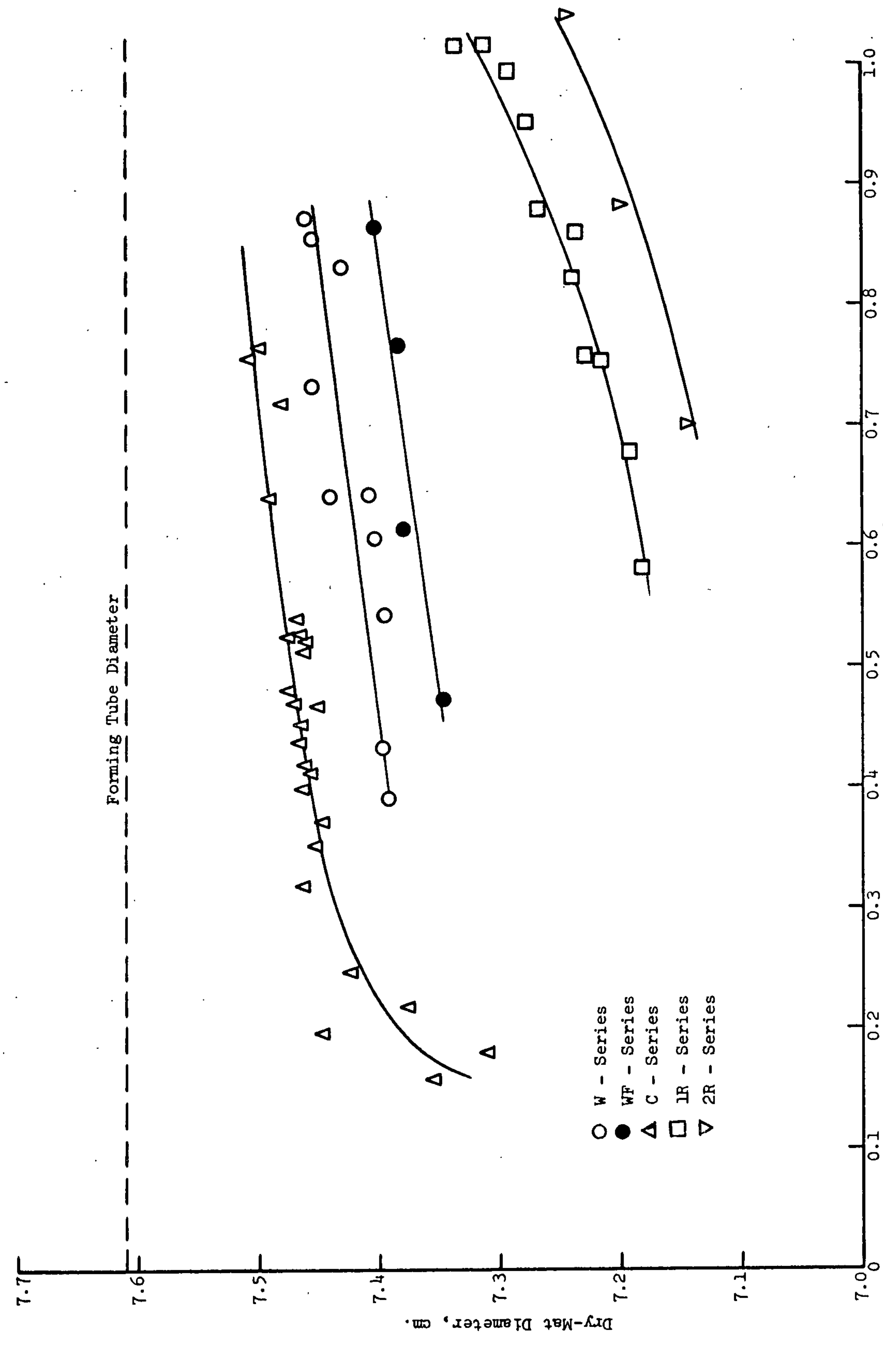

Figure 8. Dry-Mat Diameters Versus Dry-Mat Density

This would ordinarily be related to the greater potential shrinkage of the more swollen individual fibers following refining. The shrinkage is greater with refining than occurred with fines addition. One is tempted, therefore, to hypothesize that the restraint of shrinkage in drying might be more useful in increasing the modulus or flexural rigidity for those pulps which show the greater shrinkage tendency. The Setterholm and Chilson data do not tend to support this view, however.

For all pulps, the mat diameters are smaller at lower dry mat densities. One possible explanation is simply that higher wet mat compaction pressures cause more fiber deswelling and the compaction deswelling reduces the possible shrinkage in drying. Although the observation was not made directly, it appeared upon reflection that all mats did contract in diameter as a result of compaction and none expanded in diameter to the point where their removal from the restraining cylinder was difficult. If so, the greater the compaction, the greater the expected lateral contraction — an effect not reflected directly in these diameter versus density plots.

z-DIRECTION TENSILE STRENGTH

Along with the development of maximum flexural rigidity, it is necessary to develop sufficient bonding strength to permit the sheet to be further processed satisfactorily, to withstand printing stresses, etc. To some degree, such strength improvement can be obtained at the size press and through use of strength-improving beater additives, but the inherent strength of the unmodified furnish is of first interest. The z-direction tensile strength obtained with square specimens epoxy-bonded to steel surfaces is plotted versus dry sheet density on a log-log basis in Fig. 9. These data are summarized in Table VI. The relationships are similar

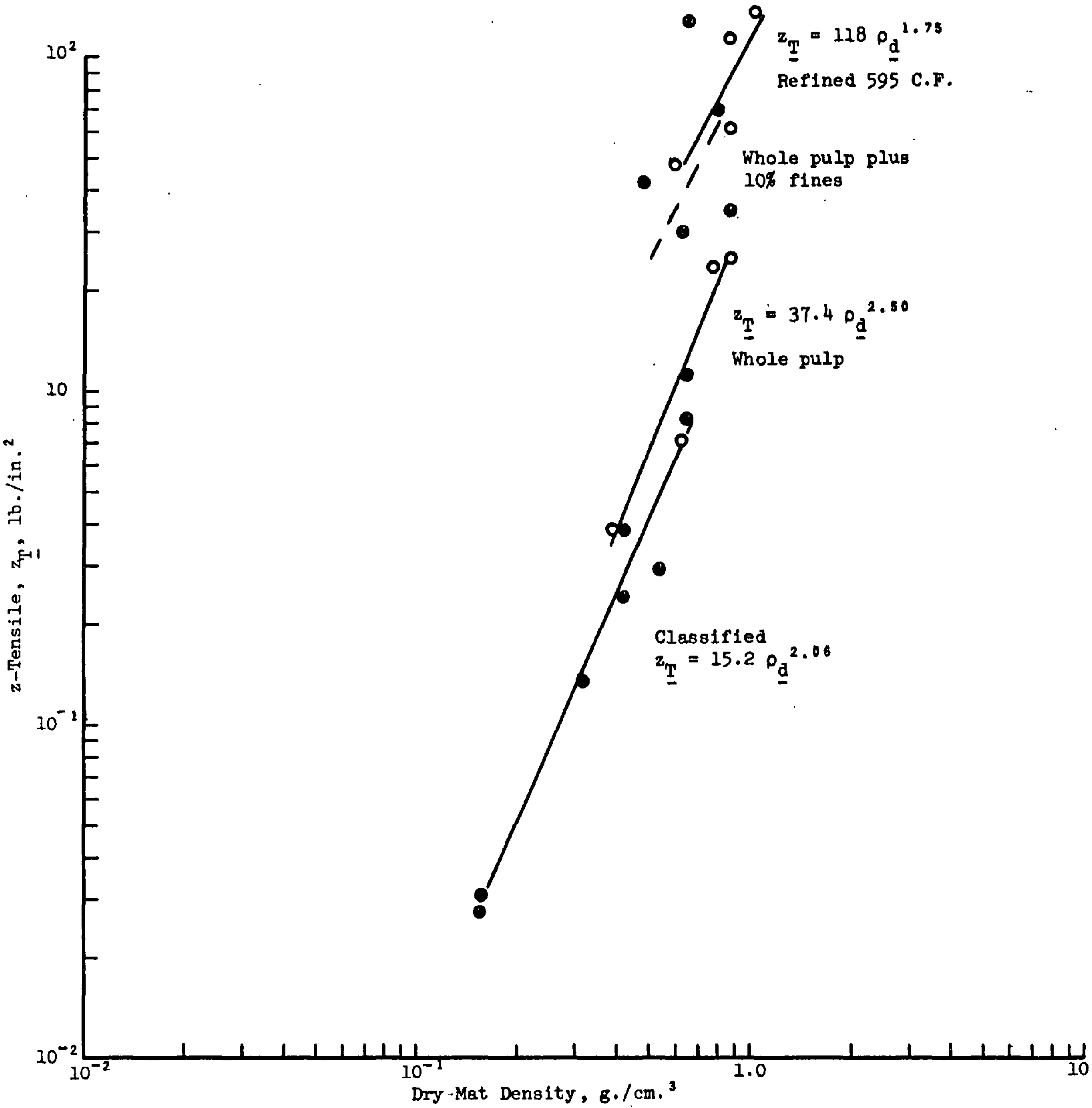

Figure 9. z-Direction Tensile Strength *Versus* Dry-Mat Density

qualitatively to those of the modulus-density plots of Fig. 6. There are some important differences, but the variability in the z-tensile data and the few samples tested make it difficult to draw firm conclusions.

The addition of fines to whole pulp resulted in a pronounced increase in z-tensile strength, which did not appear to be exceeded by the refined pulps at equivalent densities. It also appears as if the removal and addition of fines to a furnish do affect the modulus and strength differently. Much better data would be required, however, to explore these differences with confidence.

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J. P. Brezinski

J. P. Brezinski, Director

Nai L. Chang

N. L. Chang, Research Associate
Division of Materials
Engineering & Processes